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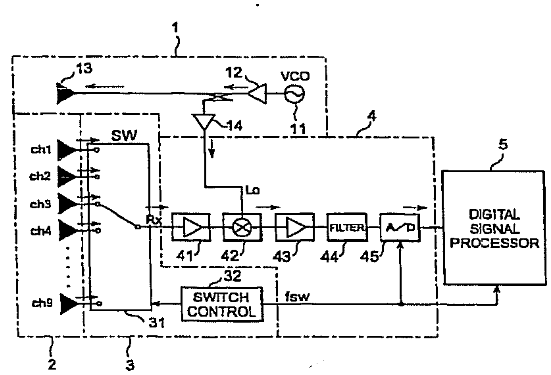
(54) FM-CW RADAR

(57) This FM-CW radar apparatus comprises a transmitter section, a receiver section, and a signal processing section. The transmitter section transmits a frequency-modulated continuous wave as a transmitted wave. The receiver section receives a radio wave resulting from reflection of the transmitted wave at a target, as a received wave, by a receiving antenna comprising an array of antenna elements, generates a beat signal which is a difference of the transmitted wave and the received wave in each of channels of the respective antenna elements, and converts this beat signal to a digital beat signal by A/D conversion. The signal processing section executes a digital beamforming operation with the digital beat signals and detects the target from the result of the operation. The receiver section has a switch means for selectively connecting either one of the antenna elements to a circuit for generating the beat signal, and this switch means connects only part of the antenna elements to the beat signal generating circuit in one period of the repetition periods of the frequency modulation.

Fig.1



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Brief Description of the Drawings

[0013]

Fig. 1 is a structural diagram to show an FM-CW radar apparatus as an embodiment of the present invention.
Fig. 2A is a graph for explaining the principle of detection of the FM-CW radar.
Fig. 2B is a graph for explaining the principle of detection of the FM-CW radar.
Fig. 3A is a graph for explaining the principle of detection of the FM-CW radar.
Fig. 3B is a graph for explaining the principle of detection of the FM-CW radar.
Fig. 4 is a flowchart to show the operation of the FM-CW radar apparatus of Fig. 1.
Fig. 5 is a timing chart to show connection timing of changeover switch 3 of the FM-CW radar apparatus of Fig. 1.
Fig. 6 is a flowchart to show procedures of the DBF synthesis.
Fig. 7 is a structural diagram to show another FM-CW radar apparatus as a second embodiment of the present invention.
Fig. 8 is a spectrum map to show a way of frequency conversion.

Best Mode for Carrying Out the Invention

[0014] Fig. 1 is a structural diagram to show a radar apparatus as an embodiment of the present invention. This radar apparatus is an FM-CW radar apparatus designed to use a frequency-modulated (FM) continuous wave (CW) as a transmitted signal and a DBF radar apparatus designed to execute the digital beamforming operation.

[0015] Prior to the description of specific structure and operation of the present embodiment, the principle of detection of the FM-CW radar apparatus will be described.

[0016] Figs. 2A, 2B, 3A, and 3B are waveform diagrams to show the principle of detection of the FM-CW radar.

[0017] Fig. 2A is a graph to show change in the frequency of the transmitted signal and change in the frequency of a received signal resulting from re-radiation from a target at the position of distance R and with the relative velocity of zero, in which the frequencies are on the vertical axis while the time on the horizontal axis. The solid line indicates the frequencies of the transmitted signal and the dashed line the frequencies of the received signal.

[0018] As seen from this graph, the transmitted signal is a modulated signal resulting from triangular frequency modulation of a continuous wave. The center frequency of the modulated wave is f0, a frequency shift width is ΔF, and the repetition frequency of the triangular wave is fm.

[0019] Fig. 3A is a graph to show change in the frequency of the transmitted signal and change in the frequency of a received signal where the target has a relative velocity V except for zero, in which the solid line indicates the frequencies of the transmitted signal while the dotted line the frequencies of the received signal. The definition of the transmitted signal and the coordinate axes is the same as in Fig. 2A.

[0020] As illustrated in Fig. 2A, when the relative velocity of the target is zero, the received signal has a time lag T (T = 2R/C : C is the speed of light) according to the distance with respect to the transmitted signal.

[0021] As illustrated in Fig. 3A, when the relative velocity of the target is V except for zero, the received signal has the time lag T according to the distance with respect to the transmitted signal and a frequency deviation D corresponding to the relative velocity. In the example illustrated in Fig. 3A, the frequencies of the received signal deviate upward in the graph, which means that the target is approaching.

[0022] A beat signal can be obtained by mixing part of the transmitted signal in such a received signal. Fig. 2B and Fig. 3B are graphs to show beat frequencies when the relative velocity of the target is zero and V (V ≠ 0), respectively, and their time axis (horizontal axis) is timed with that in Fig. 2A and Fig. 3A.

[0023] Now let fr be the beat frequency at the relative velocity of zero, fd be the Doppler frequency based on the relative velocity, fb1 be the beat frequency in a frequency-increasing interval (up interval), and fb2 be the beat frequency in a frequency-decreasing interval (down interval). Then the following equations hold.

$$fb1 = fr - fd \quad (1)$$

$$fb2 = fr + fd \quad (2)$$

[0024] Therefore, fr and fd can be computed from the following equations (3) and (4) if the beat frequencies fb1 and fb2 in the up interval and in the down interval of a modulation cycle are measured separately.

$$fr = (fb1 + fb2)/2 \quad (3)$$

$$fd = (fb2 - fb1)/2 \quad (4)$$

[0025] Once fr and fd are obtained, the distance R and velocity V of the target can be computed from the following equations (5) and (6).

$$R = (C/(4 \cdot \Delta F \cdot fm)) \cdot fr \quad (5)$$

$$V = (C/(2 \cdot f0)) \cdot fd \quad (6)$$

Here C represents the speed of light.

[0026] Since the distance R and velocity V of the target can be obtained for an arbitrary beam direction in

[0040] After completion of this operation of one A/D conversion, the flow moves to step S48. The operation from step S48 to step S57 described below is a flow of determining the sequence of the antenna elements to be connected to the receiving circuit section 4 by the changeover switch section 3. In this embodiment selection of all the antenna element channels is completed using four repetition periods of the frequency modulation.

[0041] Fig. 5 is a timing chart to show an order of selection of the antenna element channels, in which the time is on the horizontal axis. In Fig. 5, CH.1 to CH.9 indicate the connection timing of the first to ninth antenna element channels, in which high levels represent connection. A waveform 51 represents the timing of triangular modulation. For easy understanding of illustration, the connection time (high level period) of each channel is illustrated as much longer than the actual connection time in the relation to the waveform 51.

[0042] As seen from this figure, the first, second, and third antenna elements are selected in the first periodic interval and these are connected repeatedly in order. In the second periodic interval the first, the fourth, and fifth antenna elements are selected and these are connected repeatedly in order. In the third periodic interval the first, sixth, and seventh antenna elements are selected and these are connected repeatedly in order. In the fourth periodic interval the first, eighth, and ninth antenna elements are selected and these are connected repeatedly in order.

[0043] The first antenna element is always selected as a reference antenna element in the first to the fourth periodic intervals, and the second to ninth antenna elements are assigned two each to the first to the fourth periodic intervals. A beat signal based on a signal received by the first antenna element is utilized as a reference signal for phase correction in the DBF synthesis described hereinafter.

[0044] The operation from step S48 to step S57 for carrying out such changeover connection of the antenna elements is as follows.

[0045] Step S48 is to determine whether $i = 1$. If $i = 1$ then the flow goes to step S49 to replace i with $(i + (2k - 1))$. Unless $i = 1$ the flow goes to step S50 to replace i with $(i + 1)$. After that, step S51 is to determine whether i is greater than $(2 + (2k - 1))$.

[0046] Since $i = k = 1$ at present, the flow moves to step S49 to set $i = 2$ and then returns via the determination in step S51 to step S42. Then a digital beat signal of a signal received by the second antenna element is read into the buffer through steps S42 to S47. Since $i = 2$ at this point, the flow moves from step S48 to step S50 to set $i = 3$ and again returns from step S51 to step S42. Then a digital beat signal of a signal received by the third antenna element is read into the buffer through steps S42 to S47.

[0047] Subsequent to it, the flow transfers from step S48 to step S50 to set $i = 4$. Then step S51 results in making a negative judgment. Then the flow transfers to step S52 to set $i = 1$ and also set $j = 2$.

[0048] After that, the flow transfers to step S53 to compare j with N. The value N is the number of samplings in each antenna element channel in an up interval and in a down interval, and in this embodiment $N = 128$, for example. Since $j = 2$ at present, the flow returns to step S42 with $i = 1$ and $j = 2$. After that, digital beat signals of the first to the third antenna elements are read in successively before j becomes 3 in step S52.

[0049] Thereafter, digital beat signals of the first to the third antenna element channels are successively taken in similarly. After N digital beat signals have been taken in every channel, the flow moves to step S54, based on the determination in step S53, to return the value of j to "1" of its initial value.

[0050] Next step S55 is to determine whether the digital beat signal reading-in operation executed above is one in an up interval or in a down interval. Since the present status is just after completion of the reading-in in the up interval, the determination in step S55 is negative and thus the flow returns to step S42. Thereafter, digital beat signals of the first to the third antenna element channels are read in by 128 samples per channel in the down interval of the first periodic interval.

[0051] After completion of the digital beat signal reading-in operation in the down interval of the first periodic interval, the flow transfers from step S55 to step S56 to replace k with $(k + 1)$. Since $k = 1$ at present, $k = 2$ is set here and then the flow returns via the determination in step S57 to step S42.

[0052] By repeating the operation from step S42 to step S55 thereafter, the first, the fourth, and the fifth antenna elements are successively selected in each of the up interval and the down interval of the second periodic interval, as illustrated in Fig. 5, whereby the digital beat signals thereof are read in repeatedly.

[0053] When in step S56 k is set to 3, the first, the sixth, and the seventh antenna elements are successively selected in each of the up interval and down interval of the third periodic interval, as illustrated in Fig. 5, whereby the digital beat signals thereof are read in repeatedly. Further, when $k = 4$, the first, the eighth, and the ninth antenna elements are successively selected in each of the up interval and down interval of the fourth periodic interval, whereby the digital beat signals thereof are read in repeatedly.

[0054] After completion of the above processing, all the digital beat signals of the signals received by all the antenna element channels have been read in the buffer of the digital signal processing section 5. At this time, the value of k is set as $k = 5$ in step S56 and step S57 results in the positive. Thus the flow goes to step S58.

[0055] Step S58 is to execute complex FFT operation of each channel, DBF synthesis, and recognition operation of target object based on the result thereof. After step S58, the flow returns to step S41 to execute

in such structure that an IF amplifier 71 and a second mixer 72 are interposed in series between the mixer 42 and the amplifier 43 of the receiving circuit section 4 of Fig. 1. Further, it has an oscillator 73 for outputting the intermittent signals f_{IF} having the frequency equal to several ten times that of the changeover signal fsw. An example of the frequencies of the respective signals is as follows; the frequency f0 of the transmitted signal is, for example, 76 GHz, the frequency f_{IF} of the intermittent signals in an intermediate frequency band is, for example, 100 MHz, the frequency of the changeover signal is, for example, 5 MHz, and the frequency of the beat signals is, for example, DC to 100 kHz.

[0071] Fig. 8 is a spectral map to show the way of frequency conversion in the signal processing operation in the present embodiment. In the FM-CW radar apparatus of the present embodiment, a received signal 130 is replaced with signals 131 and 132 by on/off according to the intermittent signals in the changeover switch section 6 and thereafter they are downconverted to an intermediate signal 133 in the mixer 42. Subsequent to it, the intermediate signal 133 is downconverted to a beat signal 134 in the second mixer 72.

[0072] In Fig. 8, a curve 136 indicates a noise floor of the mixer 42 and a curve 136 a noise floor of the second mixer 72. As seen from this figure, the mixer 42 downconverts the signals into the IF zone where the influence of noise is low. Then the second mixer 72 having lower noise in the low frequency band than the mixer 42 downconverts the signal to the beat signal. Therefore, the present embodiment may expand the noise margin considerably, as compared with the homodyne method.

[0073] Since the mixer 42 has the very wide bandwidth, there normally appears a lot of 1/f noise and FM-AM conversion noise by the FM-CW method in the low frequency range. In contrast, since the second mixer 72 has the narrow bandwidth, the noise floor is lowered. The present embodiment achieves the expansion of noise margin by making use of such action.

[0074] If the IF amplifier 71 prior to the second mixer 72 has a narrower band, the IF signal may be separated from the FM-AM conversion noise appearing in the low frequency range, so that the low-frequency noise may be decreased further.

[0075] In the first and second embodiments the number of channels of the antenna elements was nine, but the detection accuracy may be enhanced further by increasing the number of channels.

Industrial Applicability

[0076] As described above, the FM-CW radar apparatus of the present invention needs only one set of the expensive devices necessary for the downconversion, for example, the RF amplifier, the high-frequency mixer, etc., regardless of the number of antenna elements. Therefore, the whole apparatus may be constructed at low cost and in compact size.

[0077] In addition, the switch means connects only part of the antenna elements to the beat signal generating circuit in one period of the repetition periods of frequency modulation, so that the switching frequency may be lower than in the case wherein all the antenna elements are connected to the beat signal generating circuit in one period. Further taking it into consideration that a beat signal is sampled every changeover of connection, the A/D conversion rate may also be decreased with decrease in the switching frequency. This permits use of cheaper switch element and A/D converter.

Claims

1. An FM-CW radar apparatus comprising:

   a transmitter section for transmitting a frequency-modulated continuous wave as a transmitted wave;
   a receiver section for receiving a radio wave resulting from reflection of said transmitted wave at a target, as a received wave, by a receiving antenna comprising an array of antenna elements, generating a beat signal which is a difference between the transmitted wave and the received wave in each of channels of the respective antenna elements, and converting the beat signal to a digital beat signal by A/D conversion; and
   a signal processing section for executing a digital beamforming operation with said digital beat signals and detecting said target from the result thereof,
   wherein said receiver section comprises switch means for selectively connecting either one of said antenna elements to a circuit for generating said beat signal,
   wherein said switch means connects only part of said antenna elements to said beat signal generating circuit in one of repetition periods of said frequency modulation.

2. The FM-CW radar apparatus according to Claim 1, wherein said switch means is arranged so that at least part of one antenna element or two or more antenna elements connected to said beat signal generating circuit in an arbitrary period of the repetition periods of said frequency modulation is different from one antenna element or two or more antenna elements connected to said beat signal generating circuit in another period different therefrom.

3. The FM-CW radar apparatus according to Claim 2, wherein said switch means is arranged so that all said antenna elements are connected to said beat signal generating circuit during plural periods of the

Fig.1

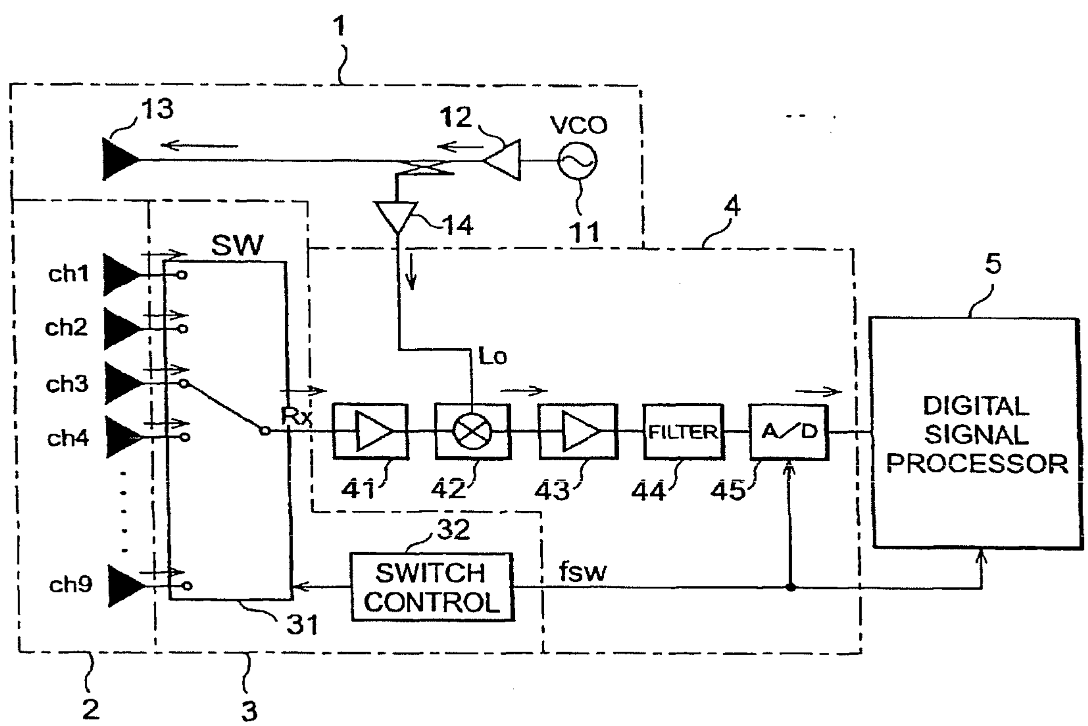

1
13
12
VCO
11
14
4
5
SW
ch1
ch2
ch3
ch4
ch9
Lo
Rx
FILTER
A/D
DIGITAL
SIGNAL
PROCESSOR
41
42
43
44
45
32
SWITCH
CONTROL
fsw
31
2
3

Fig.4

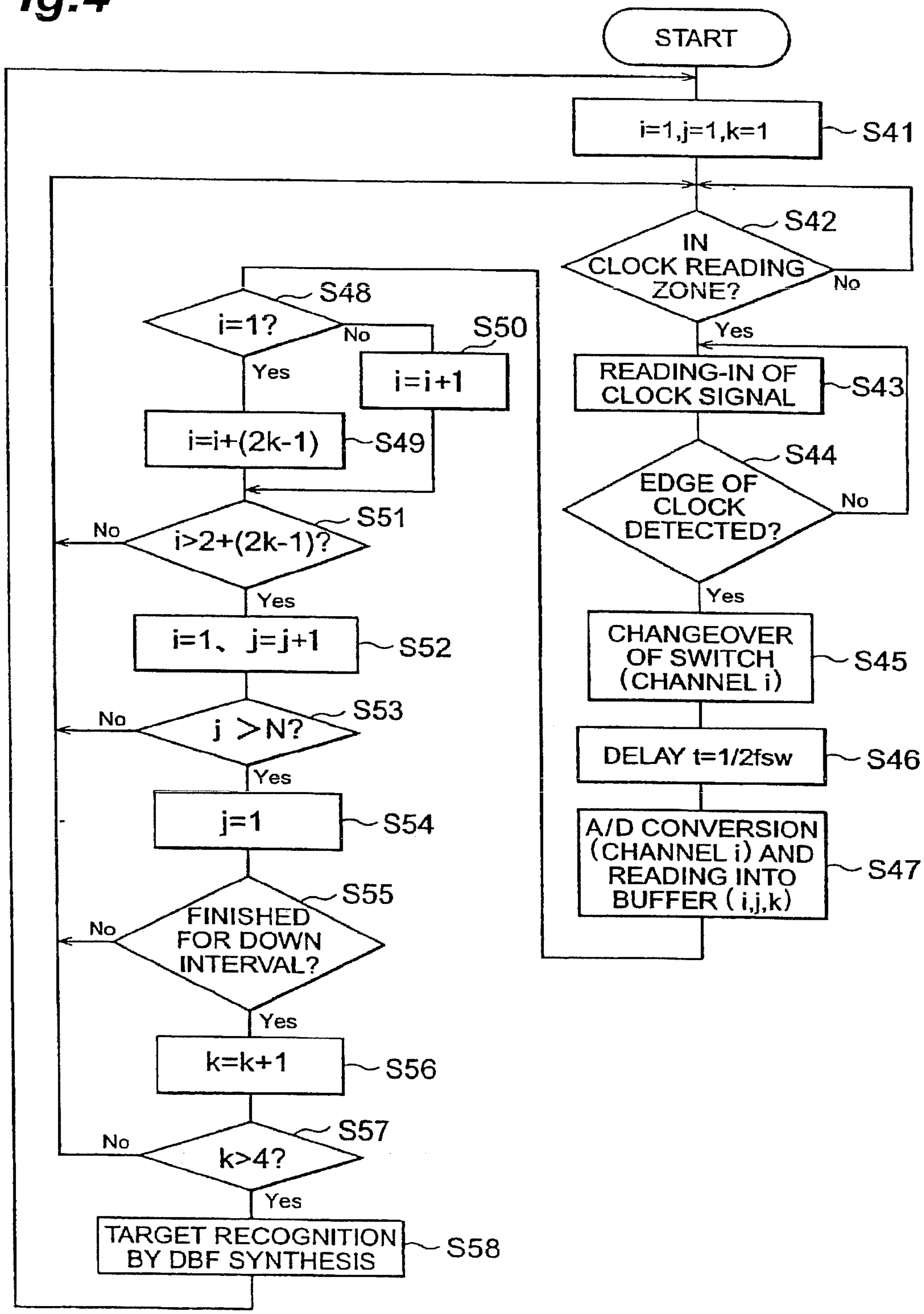

START
i=1,j=1,k=1
S41
S42
IN CLOCK READING ZONE?
No
Yes
READING-IN OF CLOCK SIGNAL
S43
S44
EDGE OF CLOCK DETECTED?
No
Yes
CHANGEOVER OF SWITCH (CHANNEL i)
S45
DELAY t=1/2fsw
S46
A/D CONVERSION (CHANNEL i) AND READING INTO BUFFER (i,j,k)
S47
S48
i=1?
No
S50
Yes
i=i+1
i=i+(2k-1)
S49
No
i>2+(2k-1)?
S51
Yes
i=1、 j=j+1
S52
No
j >N?
S53
Yes
j=1
S54
No
FINISHED FOR DOWN INTERVAL?
S55
Yes
k=k+1
S56
No
k>4?
S57
Yes
TARGET RECOGNITION BY DBF SYNTHESIS
S58

Fig.6

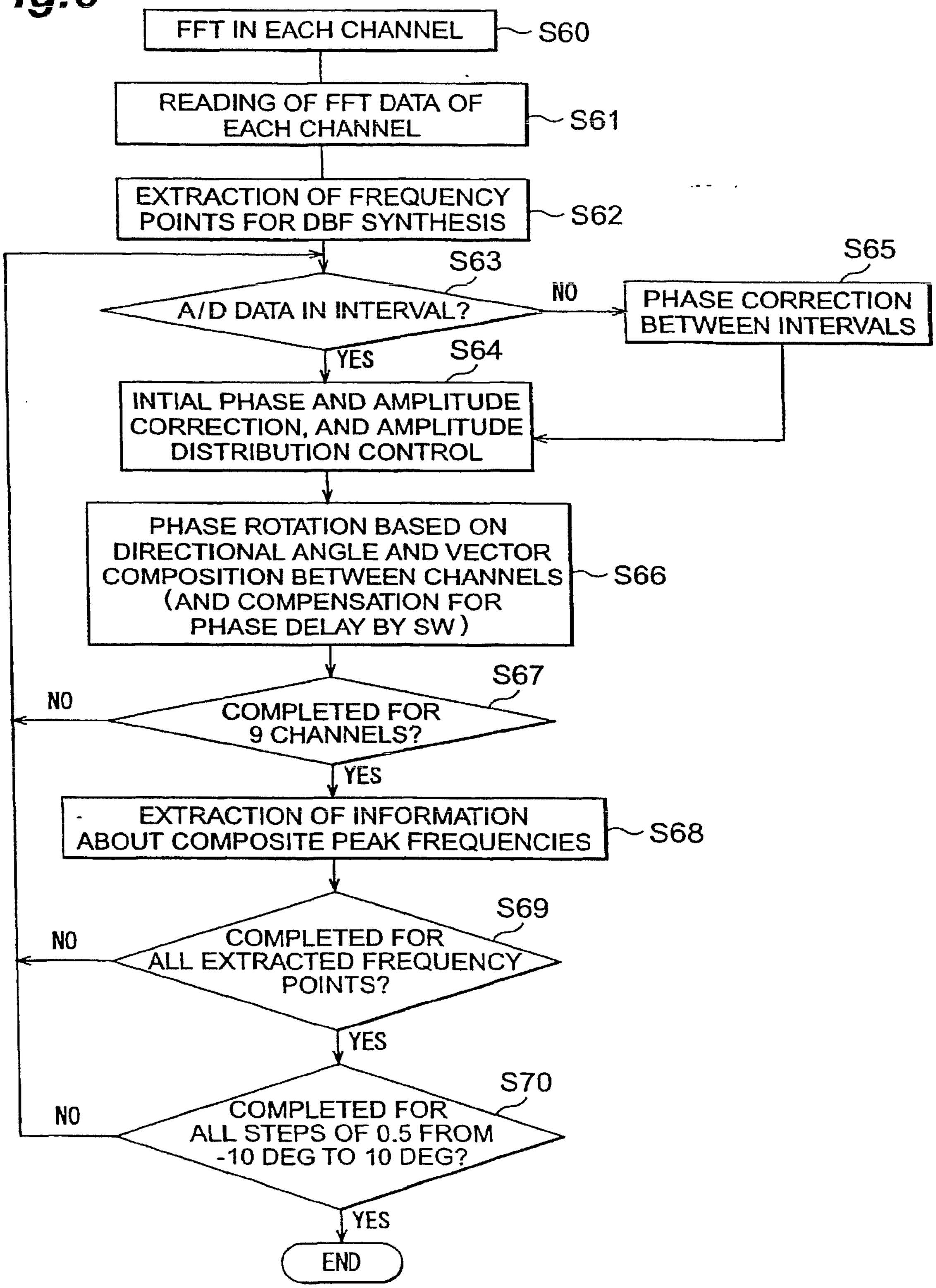
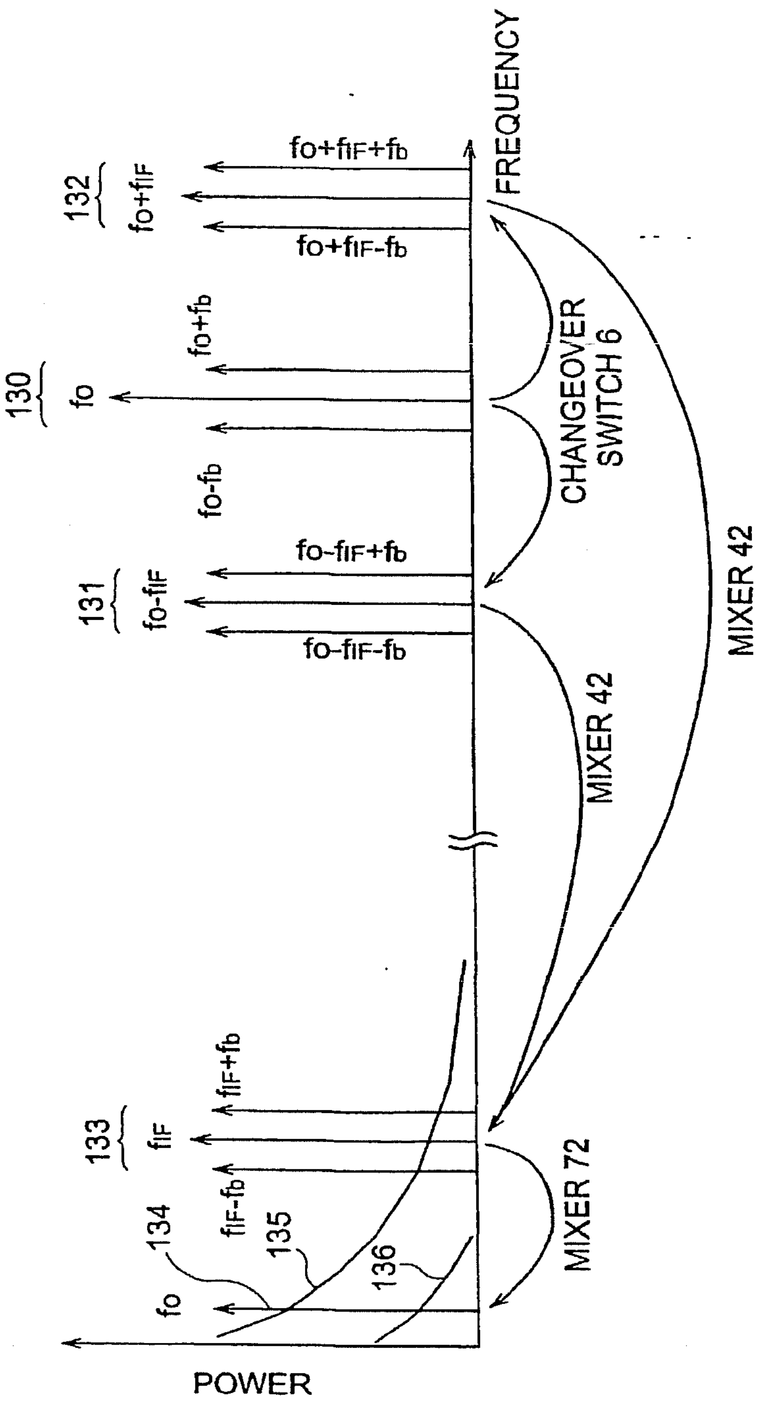

FFT IN EACH CHANNEL
S60
READING OF FFT DATA OF EACH CHANNEL
S61
EXTRACTION OF FREQUENCY POINTS FOR DBF SYNTHESIS
S62
S63
A/D DATA IN INTERVAL?
NO
S65
PHASE CORRECTION BETWEEN INTERVALS
YES
S64
INTIAL PHASE AND AMPLITUDE CORRECTION, AND AMPLITUDE DISTRIBUTION CONTROL
PHASE ROTATION BASED ON DIRECTIONAL ANGLE AND VECTOR COMPOSITION BETWEEN CHANNELS (AND COMPENSATION FOR PHASE DELAY BY SW)
S66
S67
NO
COMPLETED FOR 9 CHANNELS?
YES
EXTRACTION OF INFORMATION ABOUT COMPOSITE PEAK FREQUENCIES
S68
S69
NO
COMPLETED FOR ALL EXTRACTED FREQUENCY POINTS?
YES
S70
NO
COMPLETED FOR ALL STEPS OF 0.5 FROM -10 DEG TO 10 DEG?
YES
END

Fig.8


FREQUENCY
POWER
132
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fo+fIF
fo+fIF-fb
130
fo+fb
fo
fo-fb
131
fo-fIF+fb
fo-fIF
fo-fIF-fb
133
fIF+fb
fIF
fIF-fb
134
135
136
fo
CHANGEOVER SWITCH 6
MIXER 42
MIXER 42
MIXER 72

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP99/01484

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP, 4-313091, A (Honda Motor Co., Ltd.), 5 November, 1992 (05. 11. 92), Full text ; all drawings (Family: none)	1-3
Y	JP, 8-136646, A (Honda Motor Co., Ltd.), 31 May, 1996 (31. 05. 96), Full text ; all drawings & US, 5617098, A	4-5
A	JP, 9-222474, A (Denso Corp.), 26 August, 1997 (26. 08. 97), Full text ; all drawings (Family: none)	4-5
A	JP, 9-152477, A (Denso Corp.), 10 June, 1997 (10. 06. 97), Full text ; all drawings & EP, 777133, A & US, 5731778, A	4-5

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